

# Built-Form, Mass and Energy

## Urban fabric performance

Michele Morganti<sup>1</sup>, Anna Pages-Ramon<sup>2</sup>, Antonio Isalgue<sup>2</sup>, Helena Coch<sup>2</sup>, Carlo Cecere<sup>1</sup>

<sup>1</sup>SOSlab, Faculty of Engineering, DICEA Department Sapienza University of Rome, Rome, Italy

<sup>2</sup>Arquitectura, Energia i Medi Ambient, School of Architecture, UPC, Barcelona, Spain

*ABSTRACT: The link between urban form and building energy demand is a complex balance of morphological, constructive, utilization and climatic factor. Especially in the European compact city, where existing areas prevail on much more energy-efficient new settlements, it is evident that operative ways to transform efficiently the building stock have to be found. This paper explores the existence of a relation between built mass and energy demand depending on urban form. Focusing on the compact city of Mediterranean climate, tests on different case studies simulations are carried out. Results presented and discussed, point out that mass has strong relevance on energy demand and plays an important role in reducing energy consumptions. This paper is a preliminary report of an ongoing research study about one possible way to comprehend “metabolic rate” scaling law - the relationship between power and mass of a complex system in its process - concerning urban fabric. This knowledge-base could help verify the accordance with this rule on urban scale and give hints to conscious and effective built environment transformations towards more efficient conditions.*

*Keywords: Built-form, Energy demand modelling, Energy performance, Urban fabric, Building mass.*

### INTRODUCTION

In recent years rapid population growth in urban areas has established *city* as the first-rate contemporary human *habitat*, at the same time giving rise to some concerns about its “unsustainable” condition.

Currently it is widely known that in Europe complex activity referring to the built environment is responsible for 75% of GHG (Green House Gases) emissions and for 69% of final energy consumption [1, 2]. Recent studies agree that there is an inevitable need to reduce GHG and to take advantage of the opportunity to obtain complete self-sufficiency through renewable energy by the middle of this century [3, 4]. This is an extremely complex process simultaneously requiring improvement in energy performance in built environments, in order to reduce global energy demand.

Especially in European compact cities, new settlement models are still in negligible proportion compared to dimension of the ordinary city, in whose goal of the Sustainable Design is to be achieved. Then, it is important to have indications on the investment and effects of upgrade the built stock. Moreover it is now widely accepted that urban scale has a first rate importance in the building design process and its correlated energy performance.

Residential building stock is responsible for 65% of final energy consumption in buildings [5]. Urban form, due to the obvious connection with morphology and building systems, both at the urban and building scale, mostly affects energy performance [6]. Our aim is to

study urban fabric energy demand, beginning with building aspects. Studying building behaviour through simulations can represent one possible method in improving energy performance. Estimation of the effects of built-form on mass and energy demand is the main focus of this paper. Here we explore the existence of a relation or at least a trend, between built mass and energy demand. The purpose should be correlated to mass-energy relation of different urban fabrics.

### BACKGROUND

Recently, researchers have considered the influence of complex environmental interactions occurring in the urban context. Currently research efforts are focusing on methods and techniques for energy simulation in order to understand and, at the same time, approach different levels, from the building to urban ones [7, 8, 9, 10]. Analytical methods that allow both use at various scales and suitability to describe typologically uniform urban fabrics, are crucial in this manner.

It has been observed that scaling laws are useful in describing the complex structure of urban systems: e.g. supply networks, transport and especially energy consumption [11, 12, 13]. It is understood that modern cities have a *metabolic rate* (mass-power ratio) that approximately follows the living organism scaling laws [13]. Nevertheless, it has not been verified that this connection remains the same while studying the phenomena at the urban and building scale and what kind



Figure 1: Aerial images of case studies.

of relationship exists between mass and power, or energy depending on typologies and urban form.

Regarding the building scale, recent studies have ascertained the existence of an interaction between built-form typology and energy consumption, suggesting a classification based on chronological, dimensional and morphological factors [14].

The eventual interaction between the mass of different built-form typologies and the energy consumption has not yet been explored. Once established that mass is a parameter firmly connected to both built-form and “metabolism”, it could turn out to be the connection between typology and energy performance. This aspect is even more relevant in the context of European compact city where we can easily find urban fabrics consisting of fundamentally uniform morphological and typological elements. The latter elements, as well as the other two components of urban space - road networks and land plots - are the most influential factors of energy performance within an urban system.

### BUILT-FORM, MASS AND ENERGY AS A PERFORMANCE EVALUATION TOOL

Apart from testing the existence of a relation or a trend between building mass and energy demand, depending on built-form, our aim is to establish some key elements of a knowledge-base for future analysis on conformity with the metabolic rate scaling law at the urban scale.

Firstly, some typical urban fabrics were chosen, consisting of “conventional” typology as a basic component. Secondly, by using corresponding models, mass and energy performance were evaluated in order to ascertain suitable parameters that clearly express a connection. This study is an initial approach for using parameters (representative of built-form) as energy performance evaluation tools on a homogeneous urban texture.

### CASE STUDIES

This study compares five residential typologies, different in construction period, morphology and construction system. Focusing on the metropolitan area of Barcelona, tests through different case study simulations were carried out, to represent conventional dwelling models making up different and widespread urban fabrics built during the historical reference period (Fig. 1, Fig. 2, Table 1).

A - Historic Row House (1900) - Two level dwelling, with narrow façades of 5 m (length/width ratio  $L/W \approx 0.4$ ). The structure consists of load-bearing walls (15÷40 cm) above-ground masonry continuous foundation; dry stone drain; floors with wooden beams and brick vaulted ceiling; Catalan ventilated roof without thermal insulation.

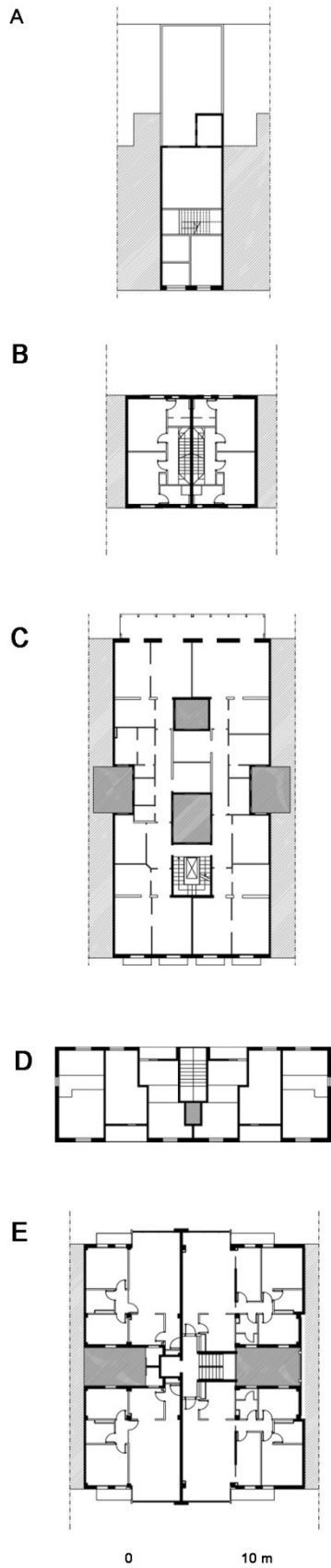


Figure 2: Plans for case studies.

B - Contemporary Row House (2000) - Three level house (and underground level) with  $L/W \approx 2$ , consisting of hollow brick load-bearing walls on concrete base slabs; external cavity walls with thermal insulation; one-way slab with ceramic filler block; flat concrete roof with thermal insulation.

C - Historic Apartment Block (1900) - We have referred to this as a typical model of the Eixample island during the first expansion period and regulated by urban ordinance. The building has six stories (height 24 m) with planned dimensions 12x24 m ( $L/W \approx 0.4$ ) and internal courtyards. As in case A, the structure consists of load-bearing walls (15÷40 cm) above-ground masonry continuous foundation; dry stone drain; floors with wooden beams and brick vaulted ceiling; Catalan ventilated roof without thermal insulation. The “galeria” of the internal façade is a typical architectural element pointed out for our interests. Depending on the façade orientation and season, it could be used as an indirect solar capitation system or as a simple balcony [15].

D - Historic Apartment Block (1960) - Nine level apartment block connected by  $L/W \approx 0.3$ . The construction system is based on 14 cm hollow bricks load-bearing walls on a concrete continuous foundation; one-way slab with ceramic filler block; external cavity walls and flat concrete roof without thermal insulation [16].

E - Contemporary Apartment Block (2000) - Six story dwelling, each dwelling faces only one side (“bilateral back to back” type) with  $L/W \approx 2$ . The structure is made up of concrete columns and two-way concrete slab; above-ground isolated footing on pile foundation and base slab; external cavity walls and flat concrete roof both with thermal insulation.

Table 1: Data for case studies

Case study	Construction period	Height/width ratio	GSI* ( $m^2/m^2$ )	FSI** ( $m^2/m^2$ )
A	1900	1.47	0.45	0.87
B	2000	0.30	0.16	0.62
C	1900	1.21	0.49	2.92
D	1960	0.41 - 1.27	0.13	0.77
E	2000	0.83	0.37	2.43

\* Coverage (GSI): built up area / base land area

\*\* Building intensity (FSI): gross floor area / base land area

## MASS AND ENERGY ANALYSIS

The methodology of this study focuses on morphological aspects relating to mass and energy performance. Therefore, the models developed mainly take into

account parameters concerning building mass and their energy demand. All other variables, except for those relating to mass and energy of different typologies, have been excluded to modelling. Consequently, to verify real influence of built-form on energy performance, we started considering only heating/cooling demands that were most directly attributable to built-form. The study does not have fully diagnostic aim, i.e. to provide exact energy demands and mass, but rather to study the value of this connection. The boundary clearly defined is the building envelope. It corresponds, in some cases, to the building studied, otherwise in other cases to the island or to part of it.

The buildings analysed are the main components of various existing urban fabrics in the European compact city. The climate of reference is the Mediterranean environment of Barcelona. In order to prevent formal and building system singularities and spatial inconsistencies of selected buildings from affecting interpretation of the results, the cases underwent a process of filtering. Conventional and coherent solutions were applied, as substitution of the original solutions, if necessary.

Mass evaluation is based on calculation of effective mass of the built elements without considering associated mass due to the construction process, which is not part of the building. The mass of supply networks, urbanizations, exterior spaces and movable elements that could be considered building elements (e.g. furniture, electrical household appliance, etc.), were not included in the calculation. All building systems were taken into account using default weight values [17]. The mass assessment process started from finding volume and density properties of different construction materials. Facing complex recent components we used the *IteC Database*, which disassembles construction elements regarding weight and material [18]. All components were grouped into building subsystems (e.g., foundation, structure, envelope, etc.), while simultaneously estimating the impacts of singular subsystems on the overall value. Results shown are expressed in metric Tons referring to thermal conditioned areas as specific weight ( $Tm/m^2$ ).

Energy demand was evaluated by modelling on *Lider* (v. 1.0 July 2009), a program associated with the Spanish Technical Building Code approved in March 2006 [19]. The derived demand values were separated into two components: heating and cooling. Taking into account eight possible orientations mean, minimum and maximum values were obtained. Modelling of all building subsystems, fixed shadows (balconies, walls, etc.) as well as internal partitions were carried out starting from detailed acquired data for each selected case. Urban obstructions were taken into account by modelling effective urban fabric geometrical properties. Concerning user dependent factors, i.e. hygrometry, ventilation rate and movable solar protections, default values were attributed. The latter is taken into account by

simulation through two solar mean reduction factors (summer and winter). *Lider* provides energy demand measured in  $kWh/(m^2 \text{ year})$ . The surface considered refers to a thermally conditioned area.

## RESULTS

The results presented and discussed are three parted. First, the building mass evaluation process is presented and analysed, then energy demand for heating and cooling is also presented, and finally their relationship is explained.

Table 2 shows the built mass referring to useful floor area. First of all we can observe that recent buildings (B - E) are heavier (expressed as specific weight) than historical buildings constructed before 1960 (A - C - D). Moreover, the apartment blocks (C - D - E) are slightly lighter per unit area than row houses (A - B). Therefore, the heavier building is case B (recent row house) while the lighter building is case C (historic apartment block).

Table 2: Built mass.

Case study	Mass ( $Tm/m^2$ )
A	1.53
B	2.58
C	1.11
D	1.24
E	1.65

The mass of the modern cases ( $Tm/m^2$  of thermal conditioned areas) is greater mainly because of mass properties in construction systems based on concrete flooring and also because of more unconditioned spaces in the buildings - especially underground car park-.

Table 3 shows results regarding annual energy demand referring to heating and cooling of different urban fabrics. Also in this parametric representation it is possible to observe a clear distinction between historic buildings (A - C - D) and recent buildings (B - E). The former have envelopes without thermal insulation, while the latter are built according to thermal regulations that restrict heat transmission coefficients (U). As further proof, case B and E have a conditioning energy demand of about  $40 kWh/m^2y$ , roughly half that of the other cases (Table 3).

Cooling energy demands of the historic urban fabric is low, 15% of heating demand, while in the case of contemporary urban fabric; cooling demand represents over 50% of heating demand. This is mainly due both to the presence/absence of thermal insulation, and to urban form properties, e.g. density, geometry, orientation. The first issue - along with modern envelopes which have

lower thermal inertia -, produces higher cooling demands, while the second affects solar radiation access. Results due to possible different orientations illustrate that variation is broader in modern building than in historic buildings. Historic buildings demonstrate similar energy performance, while contemporary buildings are more sensitive to orientation shifts. For example, case E shows great variation: the worst orientation has an energy demand 84% greater than the best orientation.

Table 3: Heating and cooling energy demand.

	Heating (kWh/ m <sup>2</sup> /year)	Cooling (kWh/ m <sup>2</sup> /year)	Heating and cooling (kWh/m <sup>2</sup> /year)		
			Average	Min.	Max.
A	86.88	3.22	90.10	86.57	93.12
B	21.85	13.32	41.04	33.17	47.01
C	79.33	8.17	87.50	85.48	89.28
D	77.52	5.74	83.26	78.29	89.28
E	22.34	11.75	39.64	25.74	47.23

Table 4 and Figure 3 show the existing tendency between mass properties and building energy demand. Referring to thermally conditioned areas, results point out that mass has strong relevance on energy, as a rough approximation described by the fitting as:

$$y = 98.952 x^{-1.998}$$

where  $y$  represents the energy demand (kWh/Tm year) and  $x$  the built mass (Tm/m<sup>2</sup> of thermal conditioned area).

Table 4: Built mass and energy demand.

Case study	Mass (Tm/m <sup>2</sup> )	Energy demand (kWh/Tm year)
A	1.53	58.9
B	2.58	15.9
C	1.11	78.9
D	1.24	67.0
E	1.65	24.1

Hence the greater the mass per conditioned square meter an urban fabric has, the less energy demand it demonstrates for heating and cooling per mass unit. Furthermore, the expression exponent near -2 suggests that mass plays an important role in reducing energy consumption (if it were -1 means that energy per unit area was constant). The reason for this should be due to the relationship between mass and energy for modern and historic urban fabrics. Modern urban fabrics have

much heavier built-form building systems (mass per conditioned unit area) and at the same time (because of thermal regulation) they have a lower energy demand.

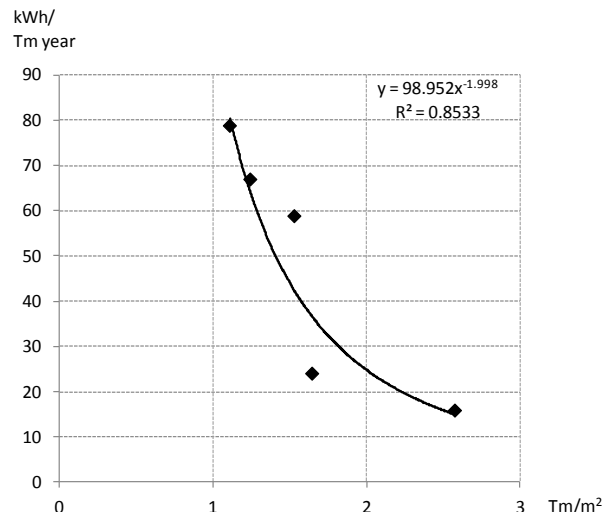


Figure 3: Relation between built mass and energy demand. Dots, computed and experimental values; continuous line, least-squares fit.

## CONCLUSIONS

This study provides a preliminary knowledge-base on finding a relationship between mass and energy consumption of different urban fabrics.

The analysis carried out on case studies prove that there is a relation between mass and energy demand (for heating and cooling) in the Mediterranean climate urban fabrics, which adopt built-form typologies and constructive systems widely spread in the Barcelona metropolitan area.

Nevertheless future studies that increase the number of case studies (without considering it part of the identification of the relationship) and expand the research field to include mass and energy, are required. Moreover for a complete comprehension of metabolism of urban fabric, more built-forms and behaviour climates should be analysed.

Other aspects are also to be considered, e.g. transport, lighting, hot water, electrical appliances, etc., which could lead to verifying accordance with this rule on the urban scale and give hints to conscious and effective built environment transformations, moving towards more efficient conditions.

## ACKNOWLEDGMENTS

This work has been supported by MICINN project ENE2009-11540. M. M. acknowledges Sapienza University of Rome for PhD fellowship.

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